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This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

Test specimens containing concrete manufactured using Type II cement conforming to ASTM Designation C-150, and shrinkage compensating cements from two producers are compared. Testing included strain measurements in slabs containing various quantities of reinforcing steel, effect of internal restraint on shrinkage and cracking tendencies, and effect of various types of restraint on the sulfate resistance of the concrete. Under the conditions of the test program there was no indication of advantage in the use of shrinkage compensated cement over conventional Type II cement that would be applicable to heavily reinforced concrete structures.

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STATE OF CALIFORNIA—TRANSPORTATION AGENCY

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DEPARTMENT OF PUBLIC WORKS

DIVISION OF HIGHWAYS

MATERIALS AND RESEARCH DEPARTMENT

5900 FOLSOM BLVD., SACRAMENTO 95819

June 1973
Final Report
D-3-38

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a research report titled:

EVALUATION OF SHRINKAGE

COMPENSATED CEMENT

Donald L. Spellman
Principal Investigator

James H. Woodstrom and
Shelly N. Bailey
Co-Investigators

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the efforts of Donald I. Nakao and Johnny L. McCormick in conducting the work for this project.

TABLE OF CONTENTS

INTRODUCTION

This study is an evaluation of shrinkage compensated cement which was commerically manufactered by two California portland cement producers. The evaluation consisted of the normal chemical and physical portland cement tests. In addition nine concrete slabs were fabricated with 0.53%, 2.41%, and 5.70% of reinforcing steel. The slabs were 4 x 4 feet square with thicknesses of 7 to 8 1/2 inches. Strain measurements were made of the steel and the concrete. Also, the sulfate resistant properties of these cements were determined.

Under conditions of the test program there was no indication of advantage in the use of shrinkage compensated cement over conventional Type II cement that would be applicable to heavily reinforced concrete structures.

CONCLUSIONS

1. Strain measurements of the biaxially restrained slabs indicated that initially, concrete made with shrinkage compensated cement expands more than ordinary portland cement concrete. Upon drying, it shrinks similarly to ordinary portland cement concrete. Under the test conditions the ordinary portland cement concrete exhibited better crack resistance than the shrinkage compensated cement concrete, though it is not certain that the cracking observed was caused by drying shrinkage.

2. The optimum percentage of biaxial restraint steel for maximum magnitude of self-stress in shrinkage compensated cement concrete seems to be somewhere between .53% and 2.41% of the cross sectional area.

3. The cross sectional area of steel commonly used in highway structures requires a greater force to elongate the steel than can be generated by the expanding concrete.

4. The crack resistance of shrinkage compensated cement, as measured by tensile strength in concrete beams positively restrained in one direction, is comparable to regular portland cement.

5. The resistance of shrinkage compensated cement concrete to attack by sulfate solutions was found to be poor, whether restrained or not.

6. Tests performed as described in this report on the modified shrinkage compensated cement indicates no improvement over the SCC tested previously.

RECOMMENDATION

1. This cement should not be used in locations where it could be exposed to sulfates.

BACKGROUND

The use of shrinkage compensated cement to produce crack-free concrete has been under investigation for some time(1,2)*. This cement consists of a mixture of portland cement and an expansive component which, when combined, induces expansion in the concrete during the early curing period. The degree of expansion depends on many factors, such as the amount of expansive component, amount and type of restraint, size and shape of specimen, and effectiveness of curing. With all other factors held constant, the expansion is generally proportional to the amount of expansive component added. Theoretically, shrinkage compensation is accomplished by restraining the expansion of the concrete by some means such as reinforcing steel, thus developing during the cure period a slight compression in the concrete and tension in the steel. On drying, this concrete will shrink similarly to regular portland cement concrete, and its residual compressive stress will be reduced. Sufficient initial compressive stresses in the concrete will prevent the development of excessive tensile stresses during the drying period, thus increasing its crack resistance.

Earlier evaluation by the California Division of Highways(3,4,5) indicated concrete with shrinkage compensated cement had no apparent advantage over regular Type II cement for use in highway structures and pavements. Laboratory tests showed that the crack resistance of restrained specimens and the freeze-thaw performance were comparable to regular Type II portland cement concrete specimens. The resistance of shrinkage compensated cement to sulfate exposure was poor, whether restrained or not.

Shrinkage compensated cement has been used in reinforced concrete for building floors and parking garages with varying success. In some reinforced slabs it has been observed that expansion or contraction joints were spaced six to seven times further apart than that normally used. Under these conditions, only minor shrinkage cracks have developed.

Refinements in the product have been indicated by manufacturer's representatives. The possibility that the modified cement could reduce shrinkage cracking in reinforced highway structures appeared promising and warranted further investigation.

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*Numbers in parenthesis refer to list of references at the end of this report.

OBJECTIVES

The work described in this report was designed to evaluate the effectiveness of shrinkage compensated cement in reducing shrinkage cracking and to evaluate its resistance to sulfate attack.

DISCUSSION OF TESTING PROGRAM

Cement

When mixed with water, expansive cement forms a paste that during and after setting and hardening increases in volume. This volume increase continues for approximately 7 days as long as the concrete is kept saturated(5).

Three types of expansive cement are presently being manufactured:

1. Type K is a mixture of portland cement compounds, anhydrous calcium sulfoaluminate ($4CaO.3Al_2O_3.SO_3$), calcium sulfate ($CaSO_4$) and lime (CaO). The anhydrous calcium sulfoaluminate (expanding component) is a compound of a separately burned clinker that is interground with portland cement clinker or it may be formed with the portland cement clinker during the burning process.

2. Type M-X is either a mixture of portland cement, calcium aluminate cement and calcium sulfate, or an interground product made with portland cement clinker, calcium aluminate clinker, and calcium sulfate.

3. Type S is a portland cement containing a large C_3A content and modified by an excess of calcium sulfate above the usual amount found in other portland cements.

There are two manufacturers of shrinkage compensated cement in California, both of which make Type K. One manufacturer makes two clinkers and combines the clinkers before grinding. This is SCC No. 1 in this report. The other manufacturer combines the raw material and makes one clinker which is SCC No. 2. SCC No. 1 contains 11%-15% expanding component and SCC No. 2 contains 10%-15%. Samples of the two different cements were obtained from the manufacturers for use in the testing program.

Type K shrinkage compensated cement is an expansive cement containing approximately 10-20 percent expansive component, which when used in restrained concrete induces compressive stresses which, theoretically at least, approximately offset or compensate for tensile stresses in the concrete induced by drying shrinkage.

Routine tests were made on the two cements as well as a Type II cement used for a control. These tests included chemical analysis, fineness, contraction, time of setting, air content of mortar, compressive strength, and autoclave expansion (see Table 1). Both shrinkage compensated cements were tested under the tentative specifications for ChemComp cement dated June 1969, prepared by the Chemically Prestressed Concrete Corporation. Tentative specifications include all the above tests except the contraction and autoclave expansion. Remarkable differences in results were noted in the latter test for the two expanding cements. SCC No. 2 had expansion of about 5/8 inch or over 6% while SCC No. 1 showed virtually no expansion. The two cement manufacturers do not agree on the significance of this test for expanding cements, with the producer of SCC No. 1 reportedly using it as a mill control test.

Reinforced Slabs

Theoretically, shrinkage compensated cement concrete must be restrained to be effective. To evaluate the cements for volume change and crack resistance under restrained conditions, nine 4x4-ft. reinforced concrete slabs were constructed. These slabs were elevated about 4 inches above the ground to represent sections of bridge decks. Three slabs were made with each of the two types of shrinkage compensated cements and a Type II cement. The slab reinforcement consisted of a double mat of steel near the top and bottom, with bars spaced at 6-inch intervals. The three slabs for each cement were reinforced with different sized reinforcing bars; No. 3, No. 7 and No. 10. Therefore, for each cement, slabs were made containing reinforcement amounting to 0.53%, 2.41% and 5.70% of the cross sectional area. Each mat had a minimum cover of 1 inch of concrete. The thickness of the slabs varied from 7 to 8-1/2 inches due to the minimum 1-inch cover requirement over the steel (see Figure 1). The aggregate was furnished by a commercial supplier in a transit mix truck. The cement was added to the truck at the construction site in an amount to obtain approximately 7 sacks per cubic yard.

Prior to fabricating the slabs comparison tests between Carlson strain gages and polyester encapsulated strain gages were made. The comparison was accomplished by casting the gages vertically side by side in a 6x12-inch concrete cylinder. Two cylinders were cast, each containing one Carlson gage and one polyester encapsulated strain gage. At the ages of 7 and 14 days the cylinders were loaded to 250, 500, 750, and 1000 psi. At each increment of loading the gages were read. Results are shown in Table 2. From the data it was concluded that the polyester gages would be satisfactory and would reduce the cost of instrumentation.

Each slab containing shrinkage compensated cement was instrumented with one Carlson and six polyester gages (see Fig. 1). The Type II cement slabs were instrumented with six polyester gages. The polyester gages were placed in two groups: one group in a bay near the center of the slab and the other in a bay near a corner of the slab. These gages were oriented to measure the concrete strain in three directions: vertical, and two horizontal directions perpendicular to each other. The Carlson gage was placed in the corner near the polyester gages and oriented to measure horizontal concrete strain only. Two micro-measurement strain gages were placed on one bar of steel in the upper mat in each slab, one near the center of the bar and one near the end, to measure the strain in the reinforcement. The slabs were constructed out-of-doors and cured with wet mats for 7 days.

The strain measurements commenced a few hours after concrete placing and continued periodically for over one year. Large discrepancies in the horizontal concrete strain readings were recorded between the Carlson strain gages and the polyester encapsulated strain gages. The polyester gages indicated tensile strains as high as 3500 micro inches/inch, which would ordinarily induce heavy cracking in the concrete. Since this did not occur it appears that some of the polyester gages were indicating incorrect strains. The micro-measurement strain gages indicate about the same strain level as the Carlson strain gages. Therefore, the Carlson strain readings will be the primary source of concrete strain data for this report.

The initial strain readings for each strain gage was taken a few hours after the concrete was placed. The change in strain for each strain gage was calculated by comparing each following strain reading to its initial reading. Concrete strains above the initial reading imply compressive stress in the concrete and strains below imply tensile stresses. Steel strains above the initial reading imply tensile stresses in the reinforcing bars and strains below imply compressive stresses.

The plotted strain data shows that during the curing period shrinkage compensated cement induces compressive stresses in the concrete and tensile strains in the reinforcing bars (see Figures 2-4). Concrete shrinkage did not occur until the concrete started to dry, approximately 2 months after casting (as indicated by the micro-measurement gages), since the slabs were cast in mid-October and stayed moist due to the wet weather. As the concrete dried the strains decreased and, in most of the slabs made with shrinkage compensated cement, dropped below the initial strain reading (zero stress), thus implying tensile stresses in the concrete and compressive stresses in the reinforcing bars. The concrete and reinforcing bars in the SCC No. 2 slab with .53% reinforcement remained above the zero stress level. The concrete in the SCC No. 2 slab with 5.70% reinforcement remained above the zero stress level although the reinforcing bars dropped below the zero stress level and experienced compressive stresses.

There seems to exist an optimum percentage of restraint as far as magnitude of self-stress and the mechanical properties of shrinkage compensated cement concrete are concerned. Concrete restrained with an amount exceeding the optimum percentage will not acquire the magnitude of self-stress acquired with concrete restrained with the optimum percentage. In early ages when the expansion is greatest, the concrete has not acquired enough strength to fully adhere to and stress large amounts of reinforcement. Therefore, slippage between the concrete and reinforcing bars probably occurs, resulting in unstressed concrete. Notice in the data plotted in Figures 5 to 10, the steel strains for the shrinkage compensated cements do not change appreciably as the percentage of steel increased from 2.41%. For percentages decreasing below .53%, the strains would probably increase drastically. Large unrestrained or partially restrained expansions may be detrimental to the mechanical properties of shrinkage compensated cement concrete[1,7]. For the 4x4-ft. reinforced slabs containing shrinkage compensated cement, the optimum percentage of restraint for maximum self-stress seems to be somewhere between .53% and 2.41%. This factor may be highly significant since bridge decks usually are designed to have about 5 to 6% steel to carry tensile loads.

Since the Carlson strain gages were omitted in the control cement slabs and the polyester encapsulated strain gages performed inadequately, the movement of the regular concrete was indirectly analyzed with the use of the steel strain data. The control concrete made with Type II cement induces slight expansive strain in the reinforcement during the curing period (Figure 2-4). As expected, regular cement concrete expands very little as compared to shrinkage compensated cement concrete. The strain was not significantly affected by the amount of reinforcement.

In spite of the above analysis some cracking of slabs was noted at an early age. The crack survey data given in Table 3 shows that cracks occurred in the slabs containing SCC No. 1 with 2.41% and 5.70% reinforcement. Cracks also occurred in the slab containing SCC No. 2 with 2.41% reinforcement. The cracks in the latter occurred on one side of the slab near the ends of the reinforcing bar. No cracks developed in the slabs containing Type II cement or the shrinkage compensated cement slabs containing .53% reinforcement. All cracks occurred within 28 days after casting. Since weather was damp and the slabs did not really start to dry out until about 2 to 3 months after casting, it seems probable that the cracks were related to factors other than drying shrinkage. They may have been caused by excessive localized expansions.

Sulfate Resistance

Earlier evaluation by this Department[5] indicated the resistance of shrinkage compensated cement to sulfate exposure was poor, whether restrained or not. Since exposure to sulfate solutions is considered as an indicator of concrete durability, the evaluation of the sulfate resistance of the new product was considered necessary.

The testing program for sulfate resistance involved placing concrete specimens out-of-doors in a shallow pond filled with a 2-1/2% ± solution of $NaSO_4$ and soil. The solution is allowed to evaporate periodically and after all free water disappears the pond is refilled with water. $NaSO_4$ is added as necessary.

Fourteen 6x6x20-inch beams were fabricated, cured for 7 days at 70°F and 100% relative humidity (RH), dried for 14 days at 73°F and 50% RH, and then placed in the sulfate exposure pond. The concrete was a 6-sack mix with 1-1/2-inch maximum sized aggregate from the American River near Sacramento. Six beams were made with each shrinkage compensated cement. Two were unrestrained, two internally restrained, and two externally restrained (see Figure 11). Two unrestrained control beams were made with a Type II cement.

The sulfate exposure beams were removed, cleaned, photographed, and returned to the exposure pond at 3-1/2 months, 6 months, and 12 months. The results are shown in Table 4 and Figures 12 to 17. SCC No. 2 is shown to be quite vulnerable to sulfate attack, much more than SCC No. 1. Externally restrained SCC No. 2 beams showed an increased resistance to sulfate attack as compared to the internally restrained and unrestrained beams. The internally restrained beams had increased resistance as compared to the unrestrained beams. No appreciable difference in resistance between the restrained and unrestrained SCC No. 1. beams were noticed. This is believed to be due to the fact that enough disintegration has not yet taken place for the restraint to be a factor. Since sulfate attack normally starts at the beam corners further exposure should show increased resistance with the externally restrained beams due to protection and end plate provides for the corners of the beam.

The "control" sulfate exposure beams were made after the shrinkage compensated cement beams were 6 months of age. After an exposure of 8 months the control beams showed very little disintegration.

Restrained Shrinkage

Earlier evaluation by this department[5] indicated that the crack resistance of shrinkage compensated cement concrete was comparable to that of regular concrete.

Reevaluation of this property involved fabricating concrete beams with internal restraint, allowing them to dry and shrink, then calculating the stress in the concrete at the time of cracking. The internal restraint consisted of a 1-1/4-inch diameter steel rod with the ends heavily threaded to achieve bond. The central 32-inch length of the rod was prevented from bonding to the concrete by a rubber sleeve (see Figure 18). A silicone lubricant was applied to this portion of the rod under the rubber sleeve to assure bond breakage. One 4-1/2x5x40-inch beam was fabricated with each of the two shrinkage compensated cements and the Type II cement for evaluation of the restrained shrinkage of the concretes. The specimens were moist cured at 73°F and 100% RH for 7 days, then allowed to dry at 73°F and 50% RH. Initial strain and temperature measurements of the bar were taken immediately after the concrete was placed into the forms. Measurements were made periodically during the curing and drying periods. The strain measurements were used to calculate the stress in the concrete at the time of measurement. The concrete was a 7-sack mix, with 1-1/2-inch maximum sized aggregate.

No tensile cracking occurred after 8 months of drying. It was assumed that the concrete would not shrink enough under the existing drying conditions to crack in tension. To accelerate drying the beams were placed in an oven maintained at approximately 100°F and 30% RH. The additional drying in the oven induced cracking in all of the beams in two days. Total days drying and calculated stress at failure are listed in Table 5. Also see Figures 19 to 21 for the plots of the data.

The shrinkage of the concrete was determined from length measurements after applying corrections for standard bar readings and temperature changes. Corrections were made accordingly from the initial measured length of the steel bar. Stresses in the concrete were computed from the shrinkage data and the following equation:

$$S_c = \frac{\Delta^1}{L} \quad \frac{A_s}{A_c} \quad E_s$$

Where S_c = Stress in the concrete

Δ^1 = Change of length of the restraining bar

L = Gage length of the restraining bar (assumed to be 36 inches)

A_s and A_c = Area of the steel and concrete respectively

E_s = Modulus of elasticity for the steel bar (30×10^6 psi)

The test results as shown in Table 5 and Figures 19 to 21 indicate that the concrete in the restrained shrinkage beams developed high tensile strengths during the testing period. The tensile strengths were larger than the tensile stresses induced by lab drying. Two days after the beams were placed in the oven, the tensile stress overcame the tensile strength, thus inducing cracking. The calculated tensile stress at failure in the SCC No. 1 beam was nearly 80 psi higher than the calculated stress in the SCC No. 2 and control beams. Since it was expected that the beams containing the shrinkage compensated cement would crack last, if at all, there is some doubt about the effectiveness of SCC in reducing cracking induced by drying shrinkage.

The physical properties of the fresh concrete used in the testing program were determined and are listed in Table 6.

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TABLE 1

REPORT OF TESTS ON CEMENT

Column Number Cement Type Laboratory Number	1 Shrink.Comp.#1 70-3708	2 Shrink.Comp.#2 70-4564	3 Type II 70-4018	4 Chem.Comp. Specificati-
Al_2O_3, %	3.7	4.5	2.8	9.0 max
Fe_2O_3, %	2.8	1.8	3.2	5.0 max
MgO, %	0.8	3.4	0.9	5.0 max
SO_3, %	5.8	6.3	1.97	8.0 max
Loss on Ignition, %	1.2	1.9	1.0	3.0 max
Insoluble Residue, %	0.4	0.3		0.75 max
Fineness, sq.cm./gm.	3803	4302	3398	2600 min
Time of Setting, Penetration				
Initial, Hrs.	>10	2.75	>2.5	>.75
Final, Hrs.	>10	7.75	<12	<10
Air Content of Motar, % by Vol.	10.8	9.4		12
Compressive Strength PSI - 3 days	2080	3400	2070	1200
7 days	2820	4320	2740	2100
Auto Clave Expansion, %	-.06	6+	-.02	
Expansion, %	.055	.1245	.0043	
Contraction, %	.0773	.0613	.0358	

TABLE 2

Carlson and Polyester Encapsulated Strain Gauges Encased in 6x12-inch Concrete Cylinders

Compressive Load (PSI)	Cylinder #1 Carlson Strain Readings (10^{-6}in/in)	Cylinder #1 Polyester Encapsulated Strain Readings (10^{-6}in/in)	Cylinder #2 Carlson Strain Readings (10^{-6}in/in)	Cylinder #2 Polyester Encapsulated Strain Readings (10^{-6}in/in)
(age 7 days)				
250	59	57	74	55
500	131	120	141	118
750	197	180	208	179
1000	282	245	294	247
(age 14 days)				
250	52	55	67	57
500	118	110	134	113
750	177	167	201	171
1000	242	227	274	230

TABLE 3

CRACK SURVEY
4'x4' Reinforced Concrete Slabs

SHRINKAGE COMPENSATED CEMENT 1	
.53% Reinforcement	No cracks.
2.41% Reinforcement	7 cracks throughout the slab.
5.70% Reinforcement	Several large cracks throughout the slab.

SHRINKAGE COMPENSATED CEMENT 2	
.53% Reinforcement	No cracks.
2.41% Reinforcement	Several large cracks located near one side of the slab, near the end of the bars.
5.70% Reinforcement	No cracks.

TYPE II CEMENT	
.53% Reinforcement	No cracks.
2.41% Reinforcement	No cracks.
5.70% Reinforcement	No cracks.

Note 1: Checking of the concrete was noticed on all slabs.

TABLE 4

SULFATE RESISTANCE BEAM SURVEYS

Beam Designation	Condition in 3 1/2 Mos.	Condition in 6 Mos.	Condition in 1 Yr.	Type of Restraint
SCC #1-IN-1	Good	Deterioration around the corners.	Mortar on upper half of the beam gone. Corners starting to crumble.	Internally Restrained
SCC #1-IN-2	Good	" "	" "	"
SCC #2-IN-1	The surface mortar around the edges & corners had started to deteriorate.	Bad deterioration around corners & edges & spreading to the top surface.	Mortar on upper half of the beam gone. Whole beam crumbling.	"
SCC #2-IN-2	" "	" "	" "	"
SCC #1-EX-1	Good	Started to deteriorate around the corners.	Mortar of the upper half of the beam gone.	Externally Restrained
SCC #1-EX-2	Good	" "	" "	"
SCC #2-EX-1	The surface mortar around the edges had started to deteriorate.	Started to deteriorate badly around the edges.	" "	"
SCC #2-EX-2	" "	The surface mortar of the upper half of the beam had almost deteriorated.	" "	"
SCC #1-UN-1	Good	Deterioration on corner & the top edge of the ends of the beam.	Mortar on upper half of the beam gone. Corners starting to crumble.	Unrestrained
SCC #1-UN-2	Good	Deterioration on corners & edges of the upper half of the beam.	" "	"
SCC #2-UN-1	The surface mortar around the edges and corners had started to deteriorate.	Deterioration spreading to surface of beam.	Whole beam crumbling, large cracks on bottom of the beam. Botton of the beam appears to be expanding.	"
SCC #2-UN-2	" "	Surface mortar of the upper half of the beam had deteriorated.	" "	"
Control-1	Good	Surface mortar around the edges, corners & top surface had started to deteriorate.	*	"
Control-2	Good	Surface mortar around the edges & corners had started to deterior[illegible]	*	"

*[illegible]

TABLE 5

RESTRAINED SHRINKAGE DATA

Beam Designation	Failure Days Drying	Type of Failure	Calc. Conc. Stress at Failure (PSI Tension)	28 Day Compressive Strength (PSI)
SCC #1	233*	Tensile	562	5310
SCC #2	233*	"	486	5320
Control	233*	"	486	5910

*Last two days was oven drying at 100°F and 30% relative humidity.

TABLE 6

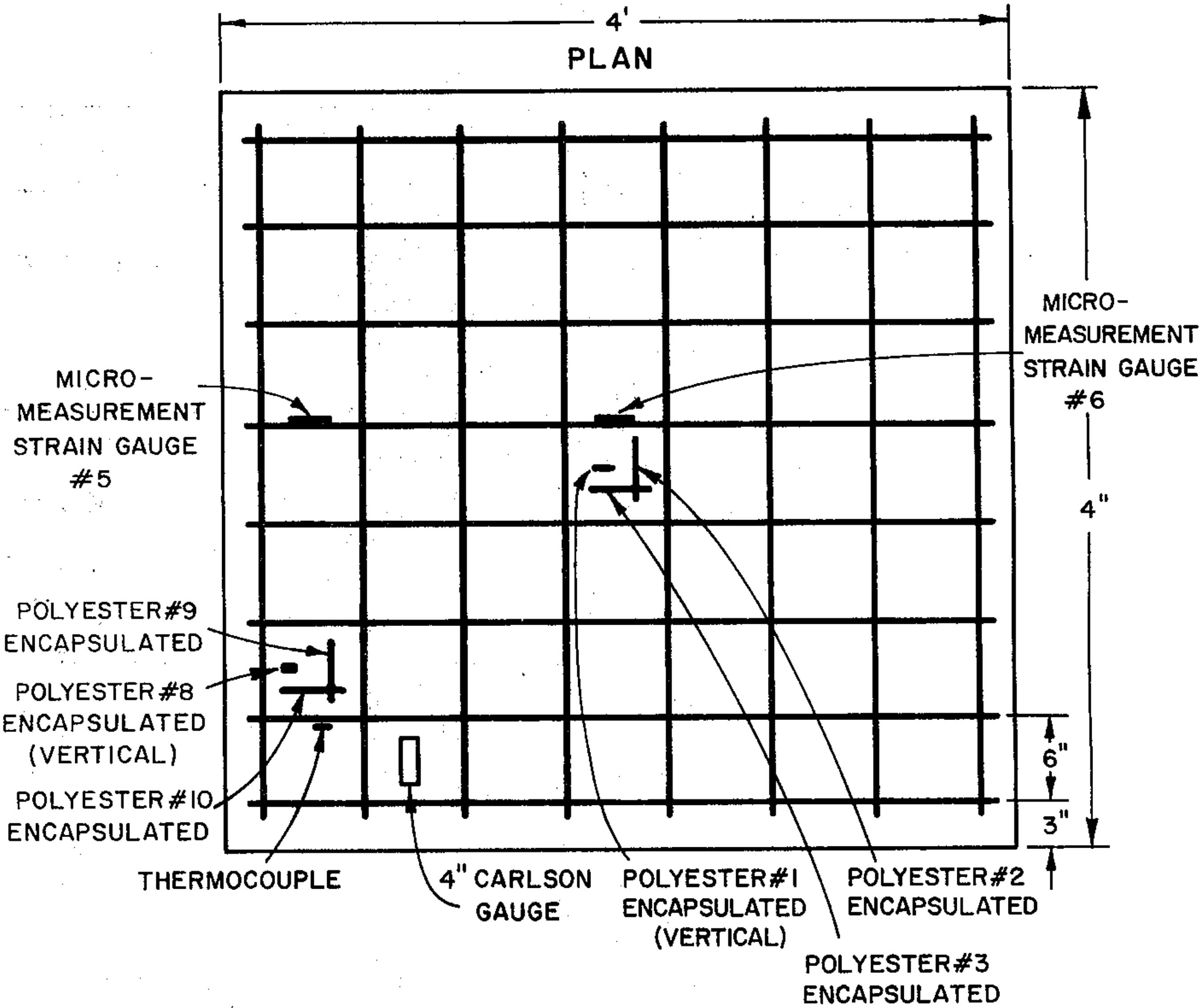
PHYSICAL PROPERTIES OF THE FRESH CONCRETE MIXES

Series	Type of Cement	Slump Ins.	Air %	Unit Wt. Lbs./CF	Net W/C Lbs./SK	Cement Factor SK/CY
4x4-Ft. Rèinforced Slabs	SCC #1	5	1.1	148.7	-	Approx.7*
	SCC #2	4 1/2	0.8	150.1	-	"
	Control	4	0.9	149.2	-	"
Beams for Sulfate Resistance	SCC #1	3	1.2	156.4	43.4	6.20
6x6x20-In.	SCC #2	4	1.4	155.2	44.4	6.14
	Control	5	0.8	156.3	44.1	6.18
Restrained Shrinkage Beams	SCC #1	3 1/2	1.4	155.4	40.5	7.27
4.5x5x40-In.	SCC #2	5	1.4	154.6	43.4	7.19
	Control	4	1.4	155.4	41.8	7.25

*Aggregate was from commercial supplier and arrived in a transit mix truck. The cement was added at the construction site by Lab personnel.

Figure 1

SLAB REINFORCEMENT AND INSTRUMENTATION



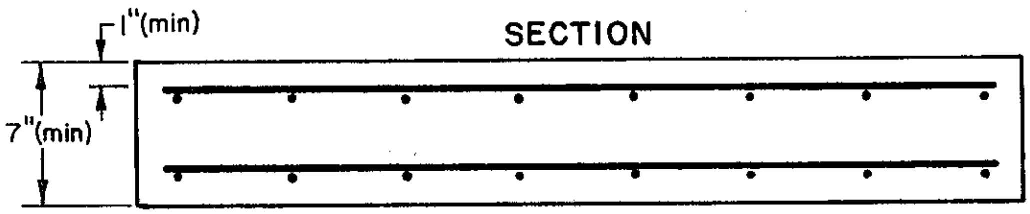
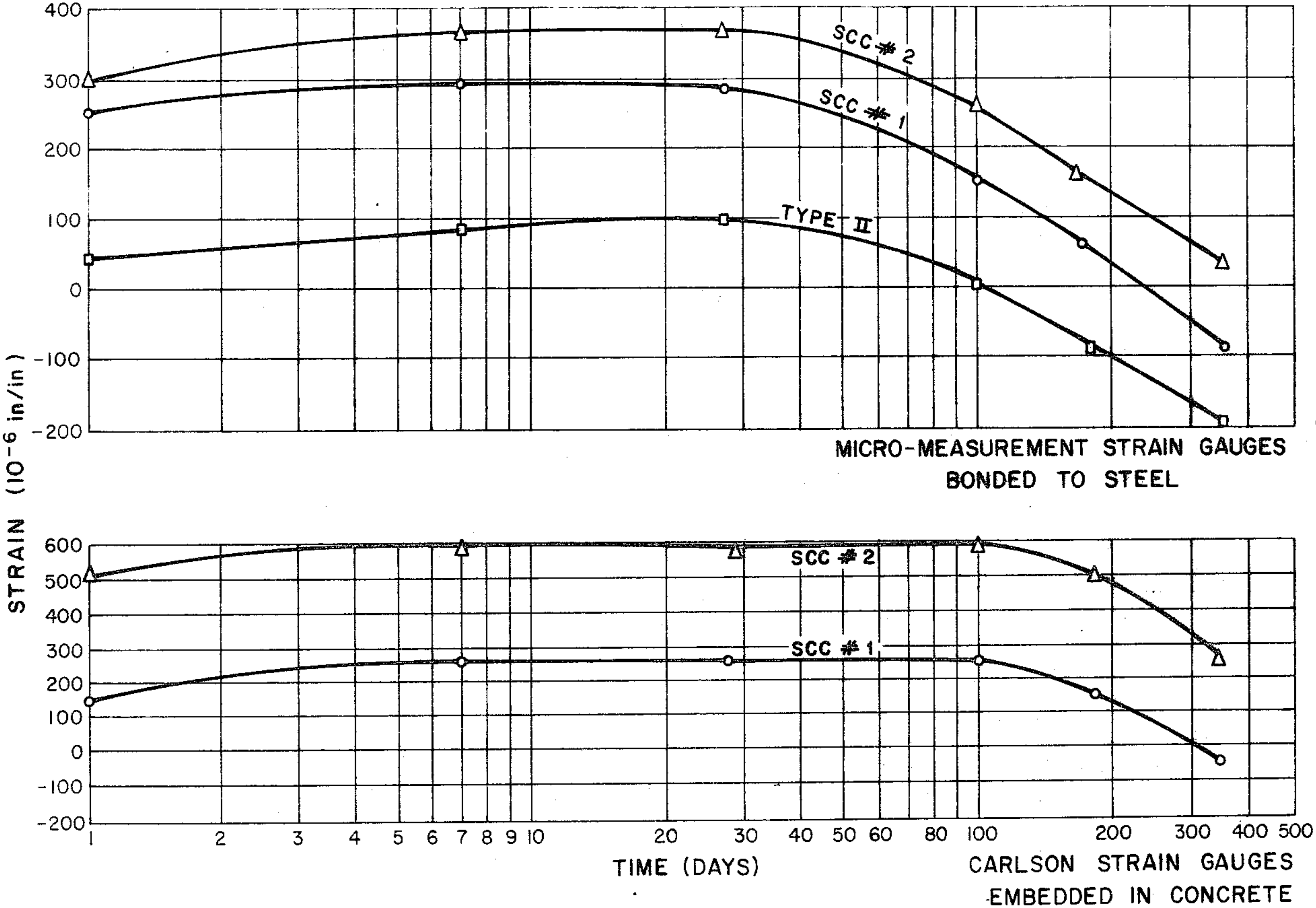
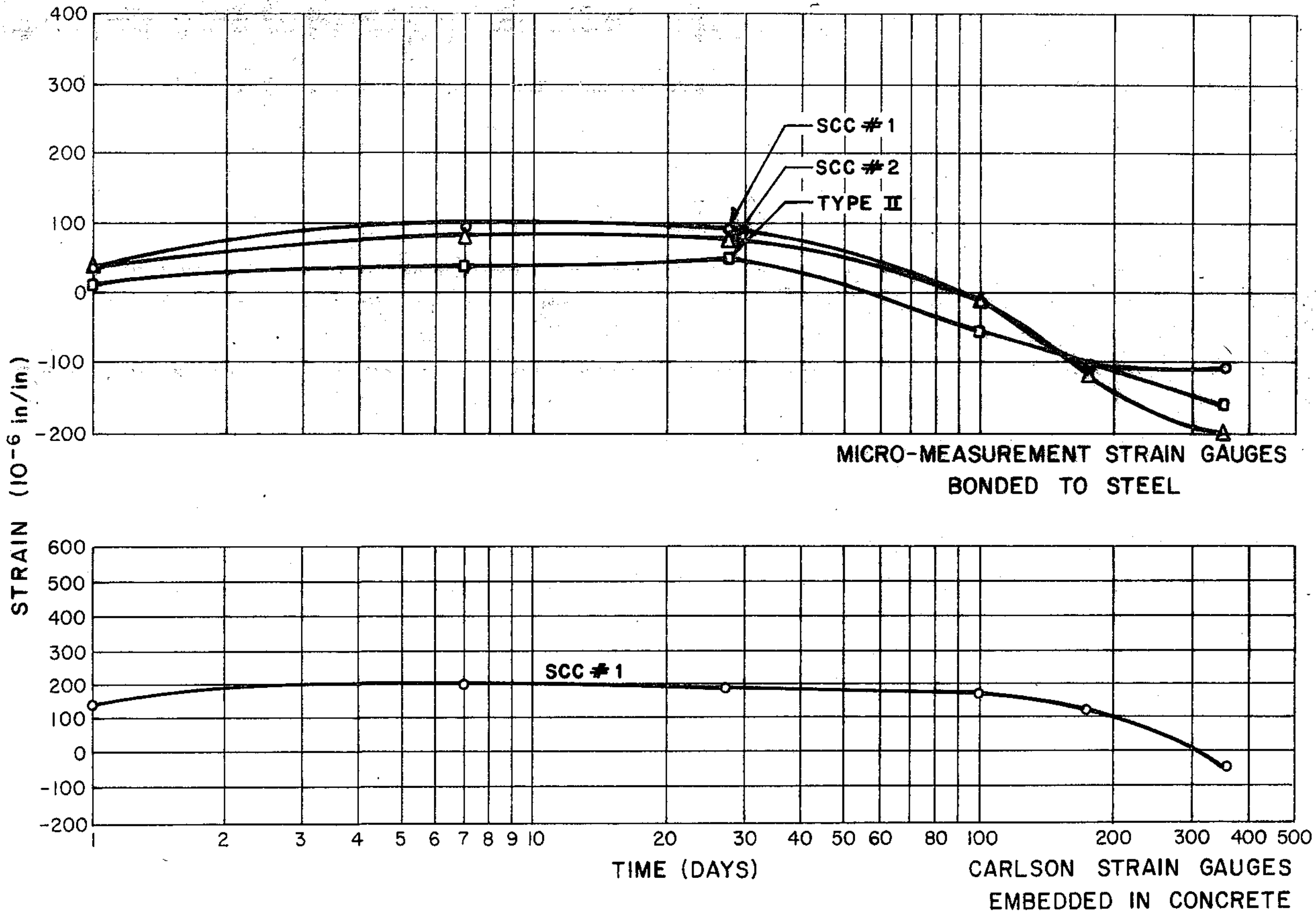


Figure 2



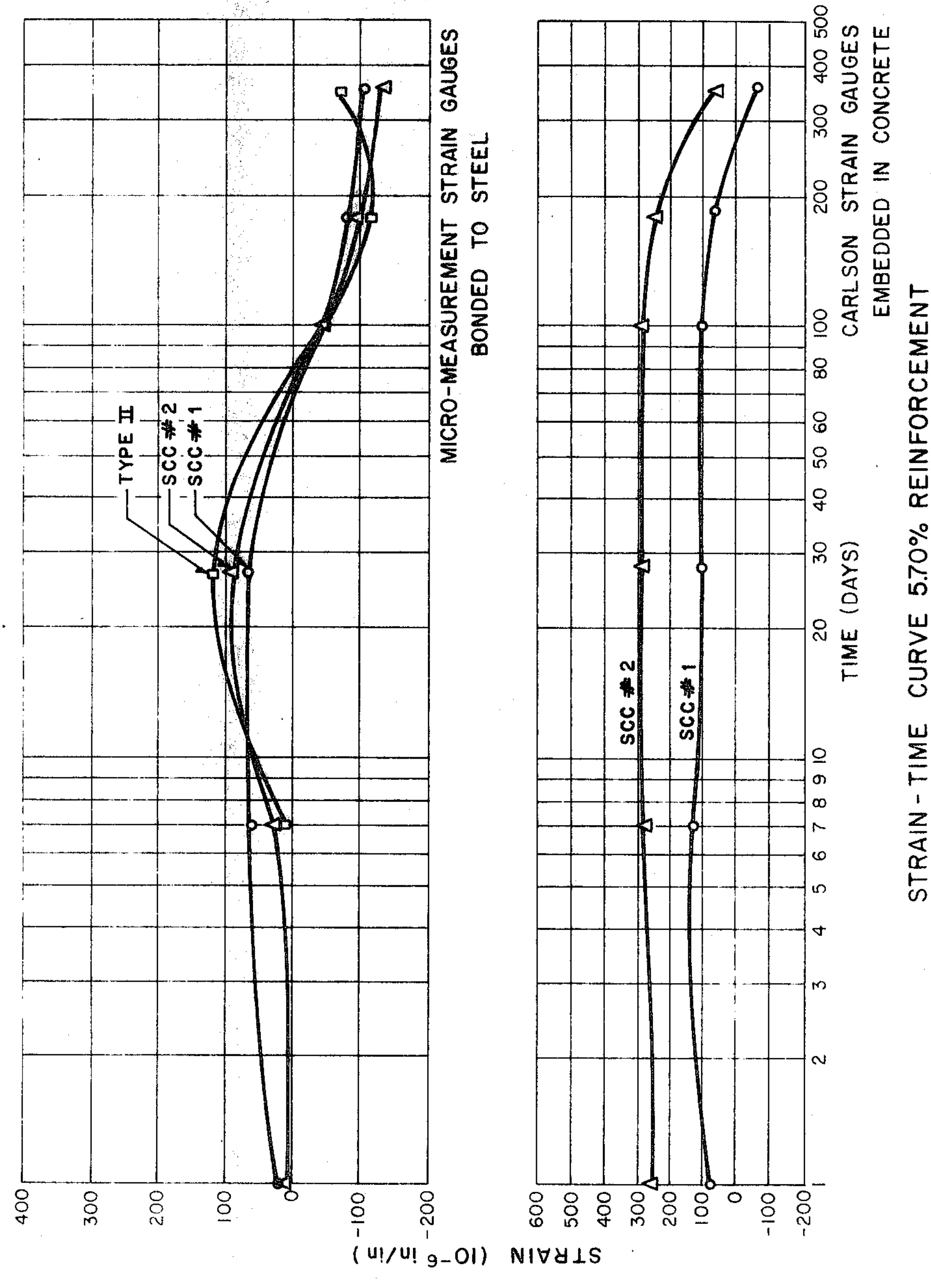
STRAIN - TIME CURVE 53 % REINFORCEMENT

Figure 3



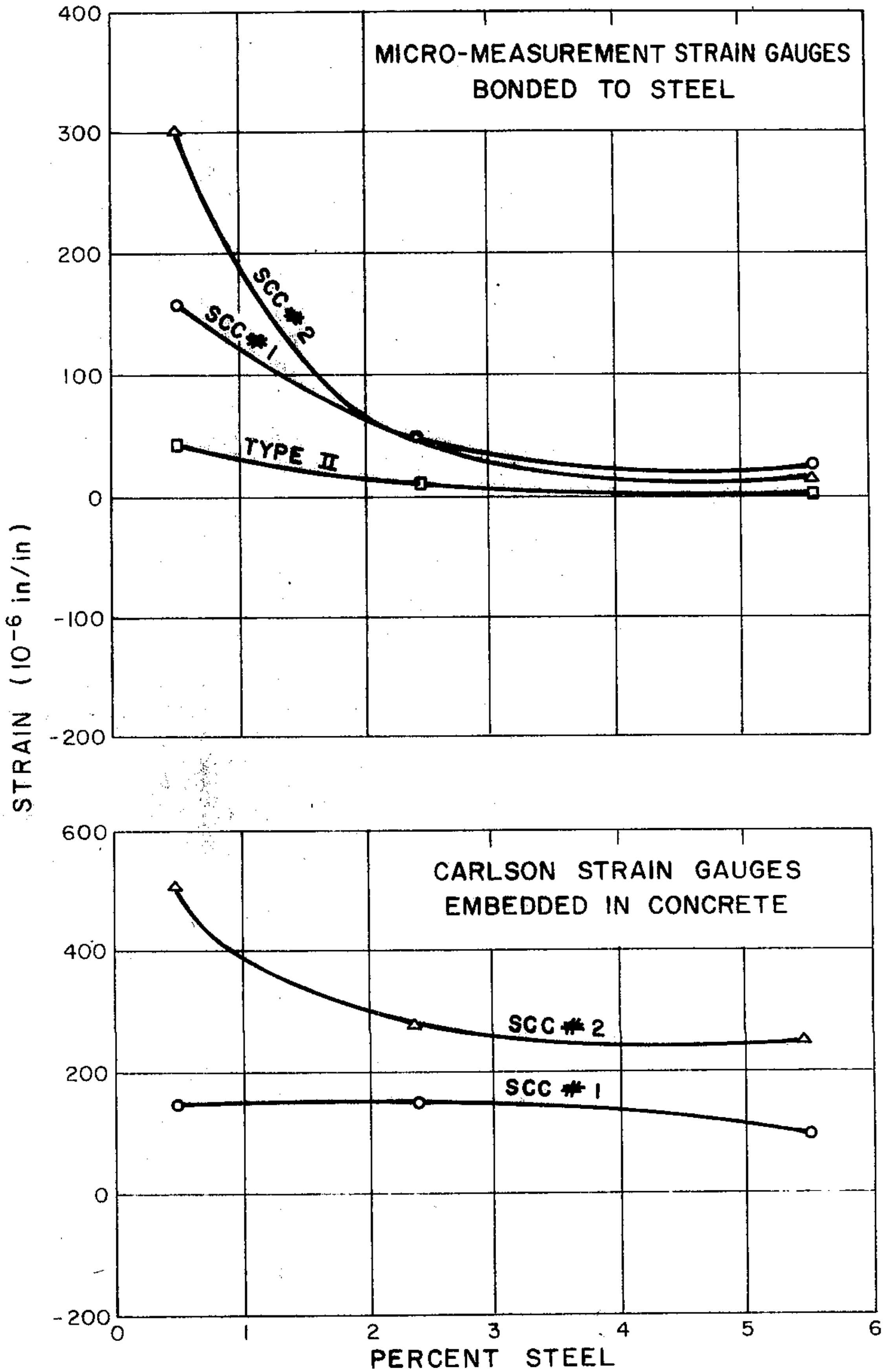
STRAIN - TIME CURVE 2.41% REINFORCEMENT

Figure 4



STRAIN - TIME CURVE 5.70% REINFORCEMENT

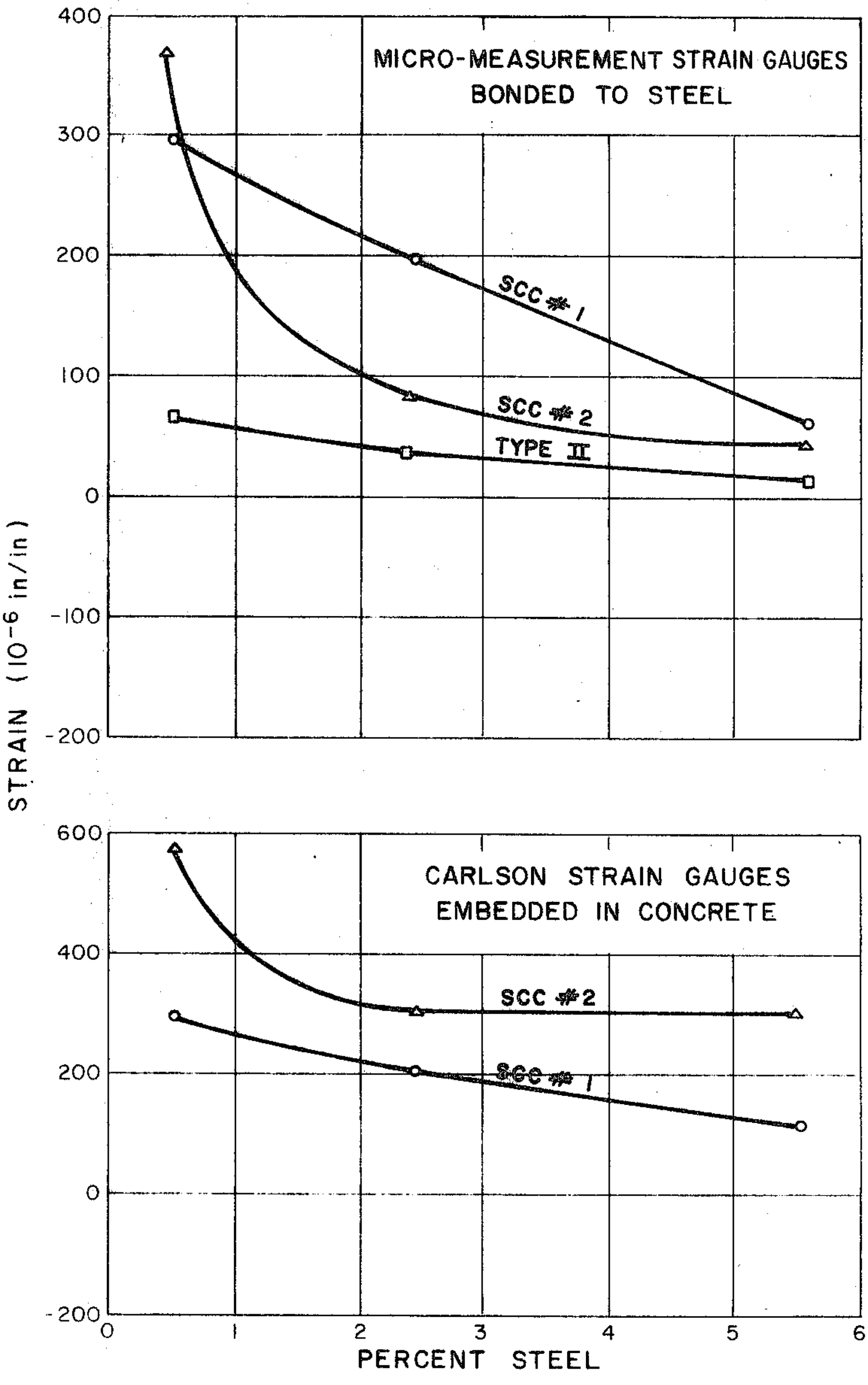
Figure 5



AGE 1 DAY

STRAIN VS PERCENT STEEL

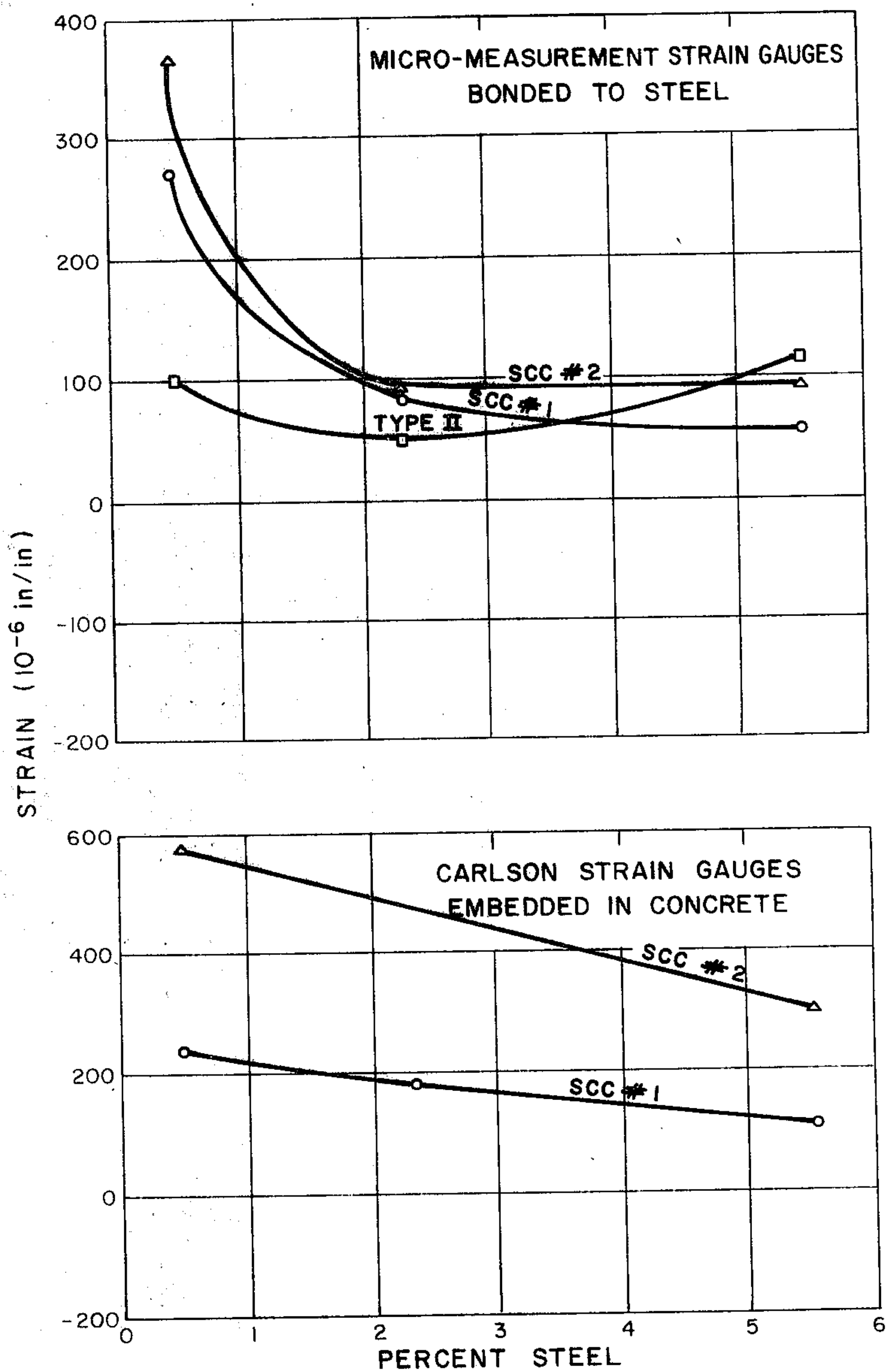
Figure 6



AGE 7 DAYS

STRAIN VS PERCENT STEEL

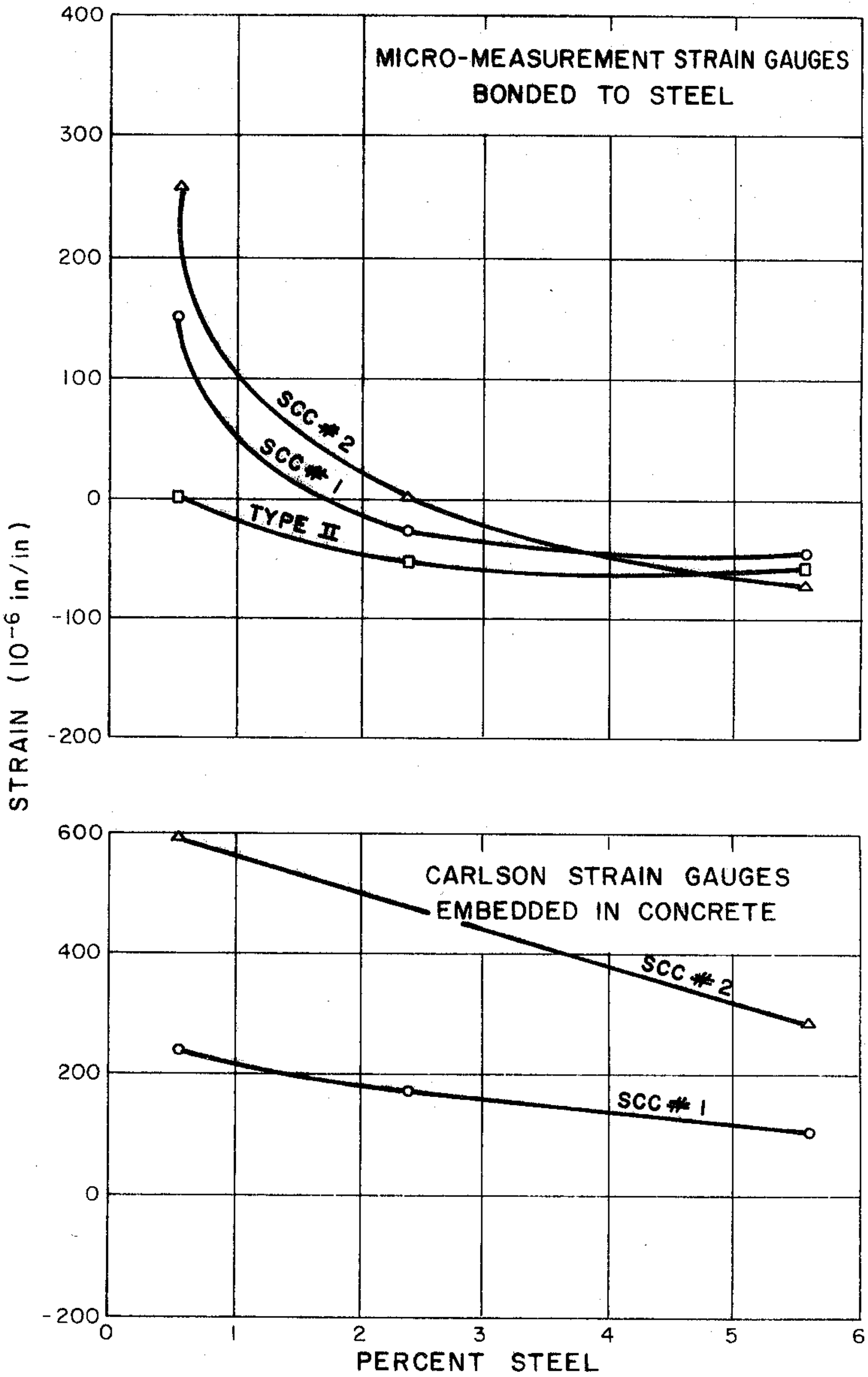
Figure 7



AGE 28 DAYS

STRAIN VS PERCENT STEEL

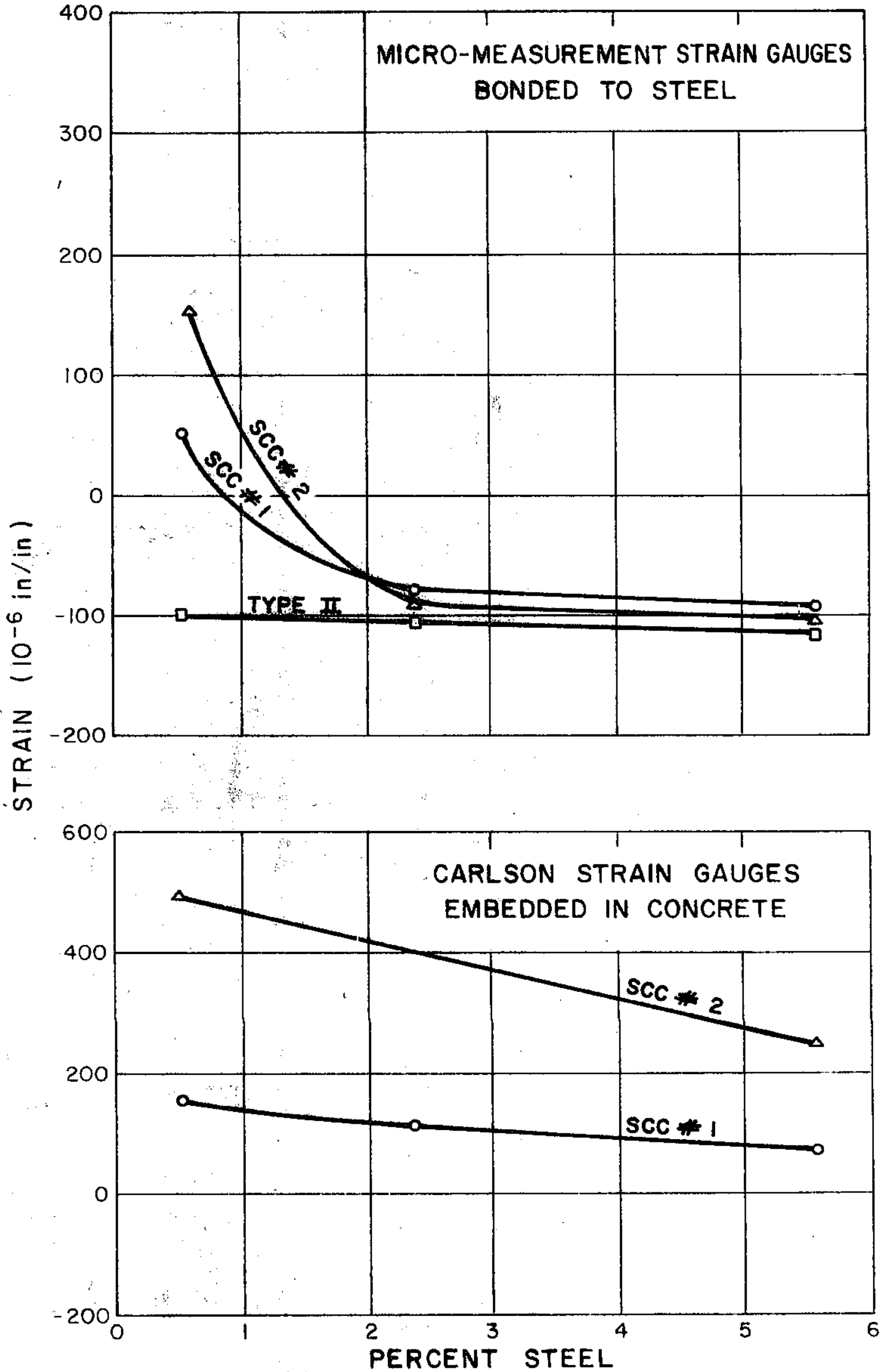
Figure 8



AGE 100 DAYS

STRAIN VS PERCENT STEEL

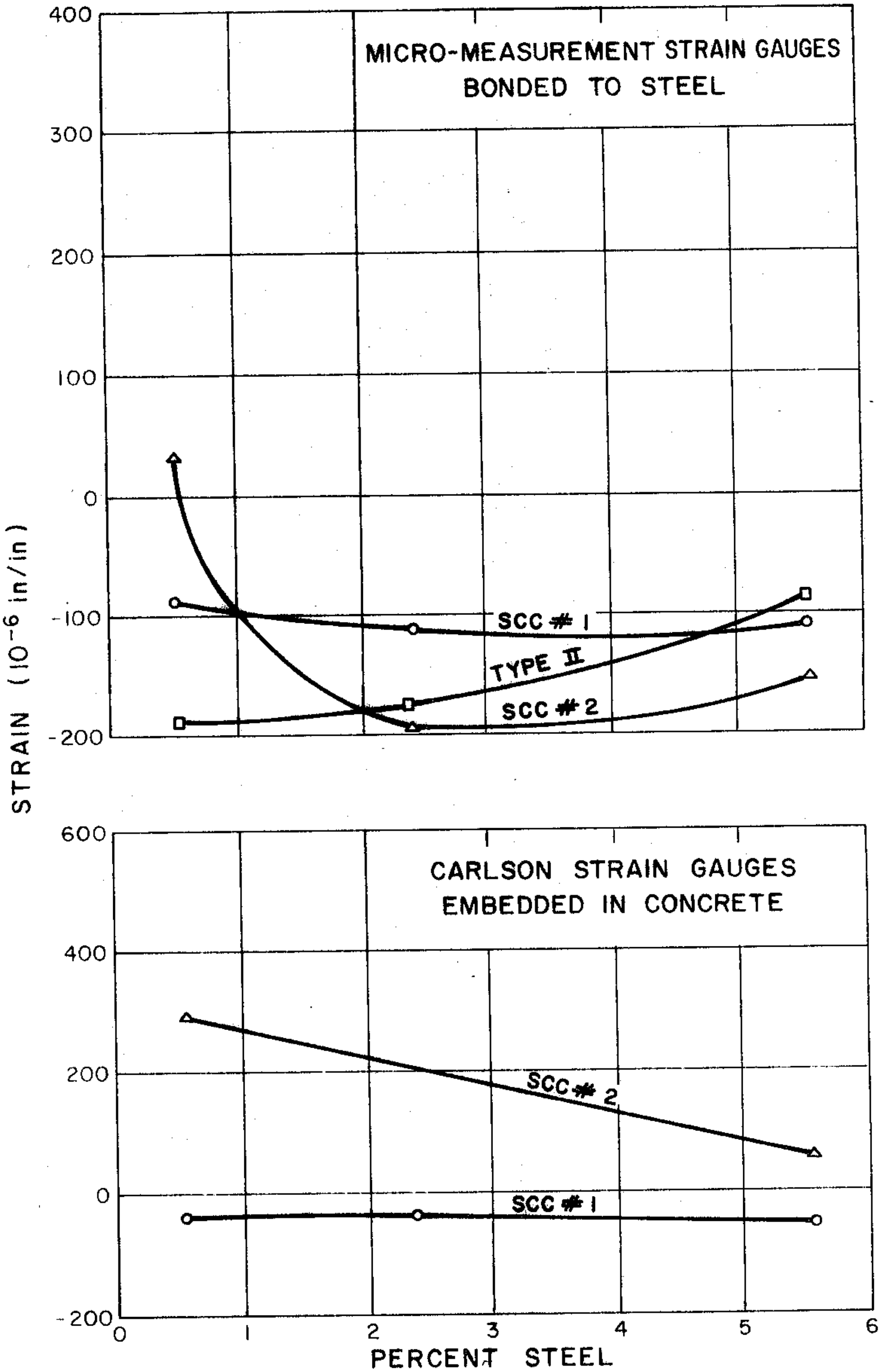
Figure 9



AGE 180 DAYS

STRAIN VS PERCENT STEEL

Figure 10

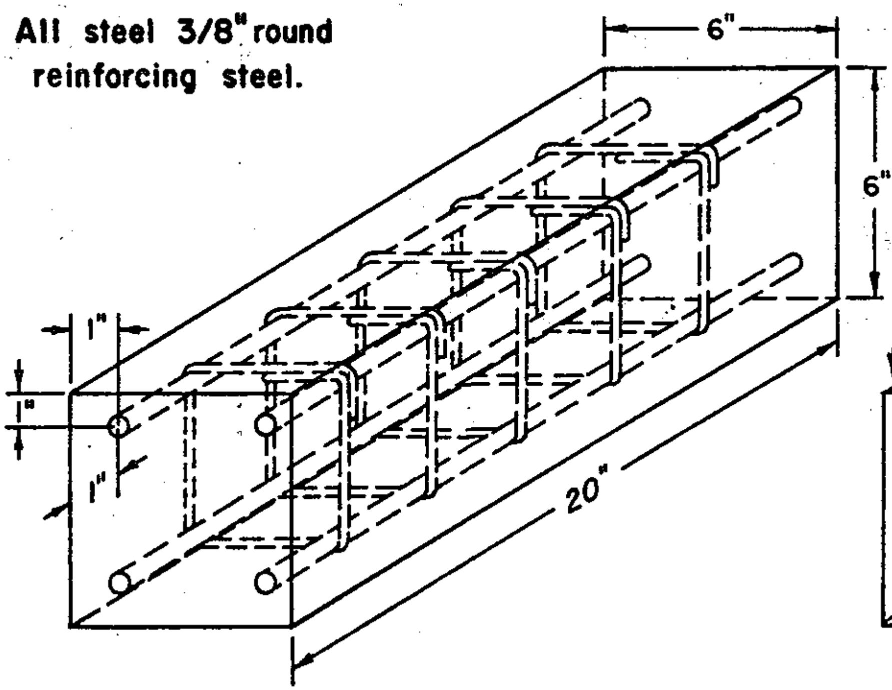


AGE 365 DAYS

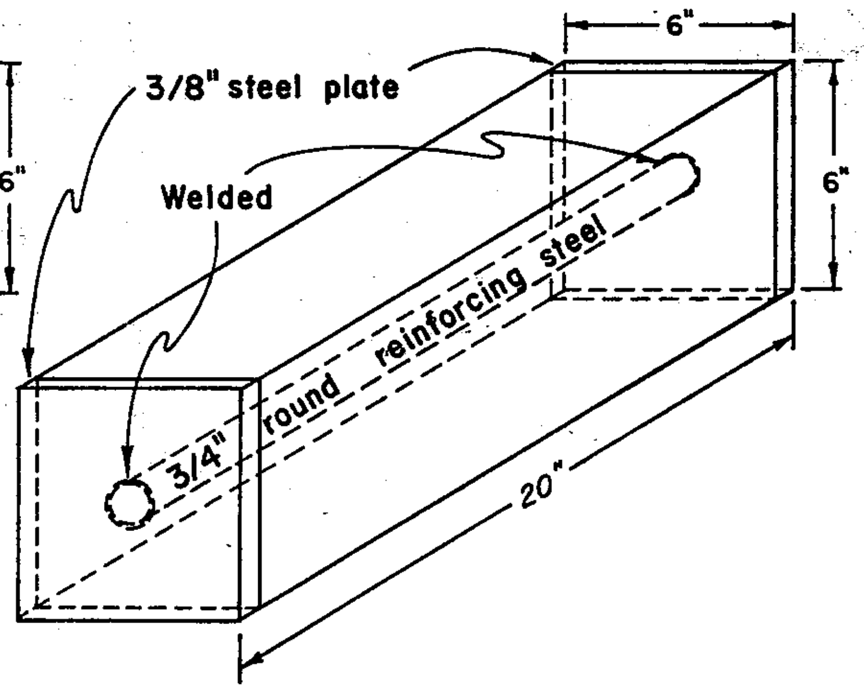
STRAIN VS PERCENT STEEL

Figure 11

SKETCH OF RESTRAINED SULFATE EXPOSURE BEAMS



INTERNALLY RESTRAINED



EXTERNALLY RESTRAINED

Figure 12. Externally restrained concrete beams made with shrinkage compensated cement no. 1 after 1 yr. sulfate exposure.

Figure 13. Externally restrained concrete beams made with shrinkage compensated cement no. 2 after 1 yr. sulfate exposure.

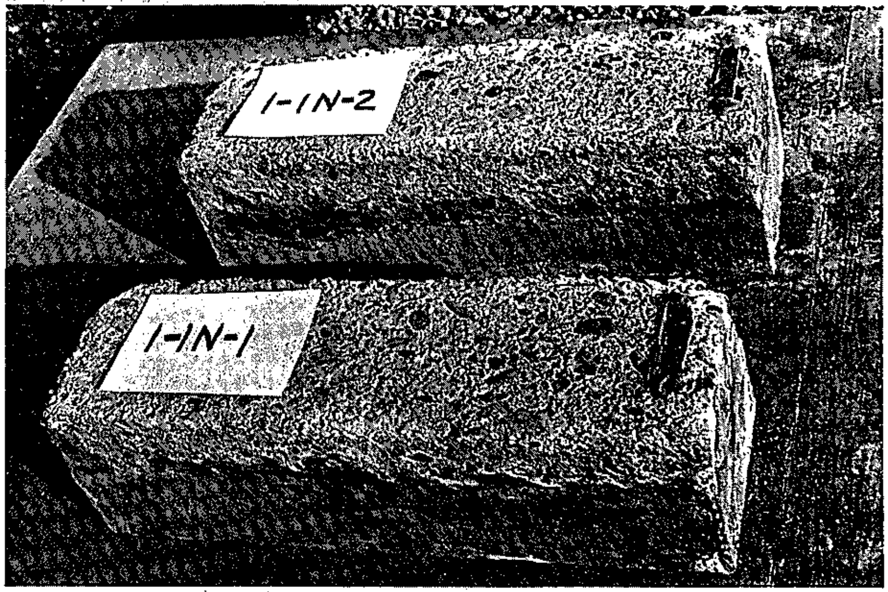


Figure 14. Internally restrained concrete beams made with shrinkage compensated cement no. 1 after 1 yr. sulfate exposure.

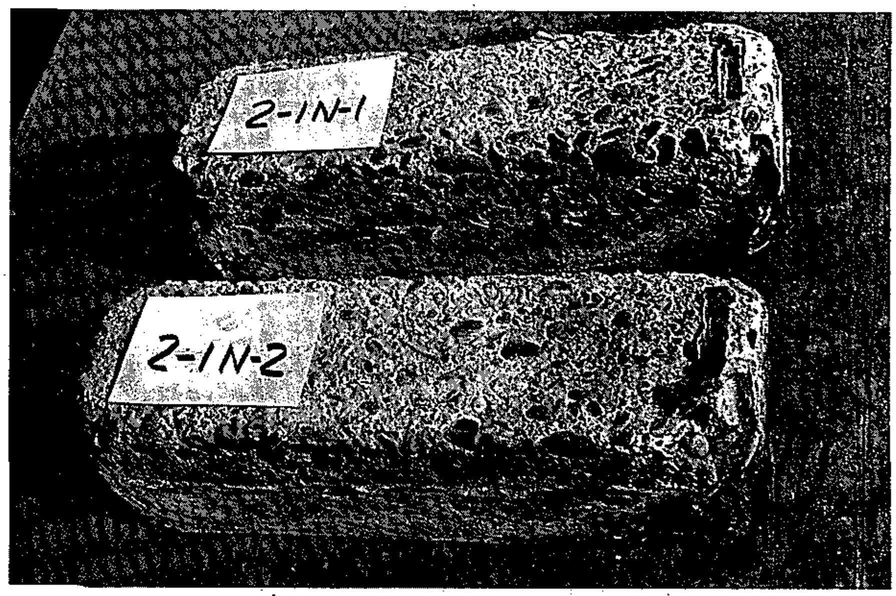


Figure 15. Internally restrained concrete beams made with shrinkage compensated cement no. 2 after 1 yr. sulfate exposure.

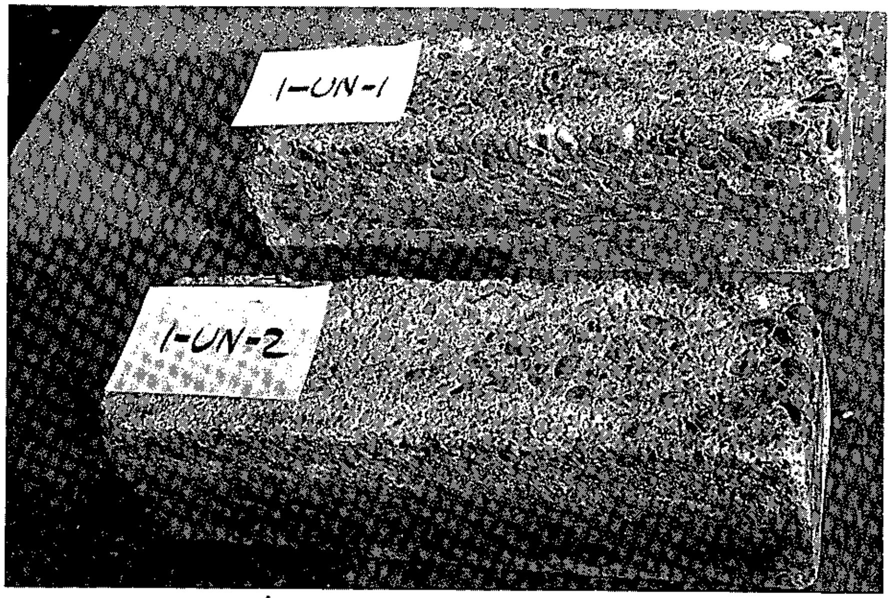


Figure 16. Unrestrained concrete beams made with shrinkage compensated cement no. 1 after 1 yr. sulfate exposure.

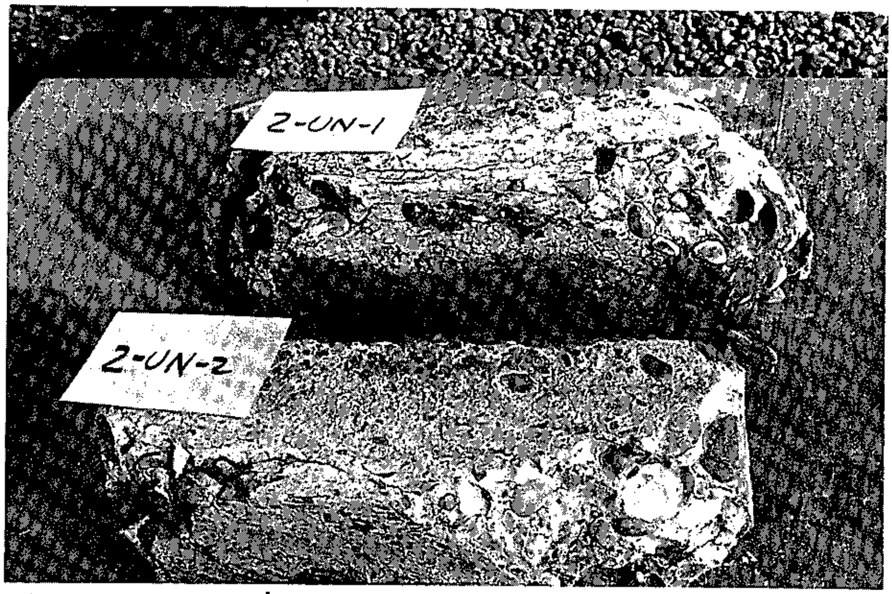
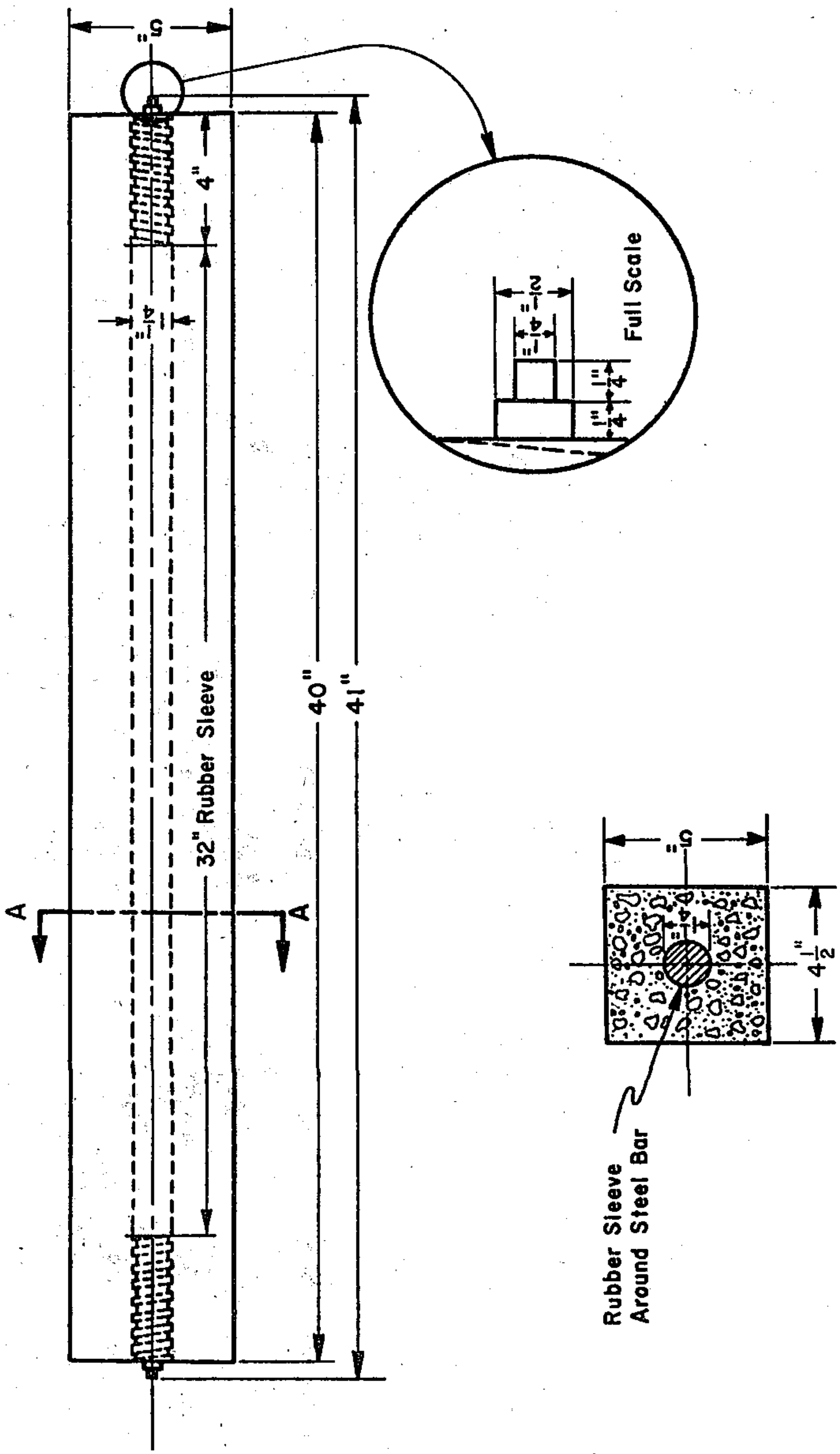


Figure 17. Unrestrained concrete beams made with shrinkage compensated cement no. 2 after 1 yr. sulfate exposure.

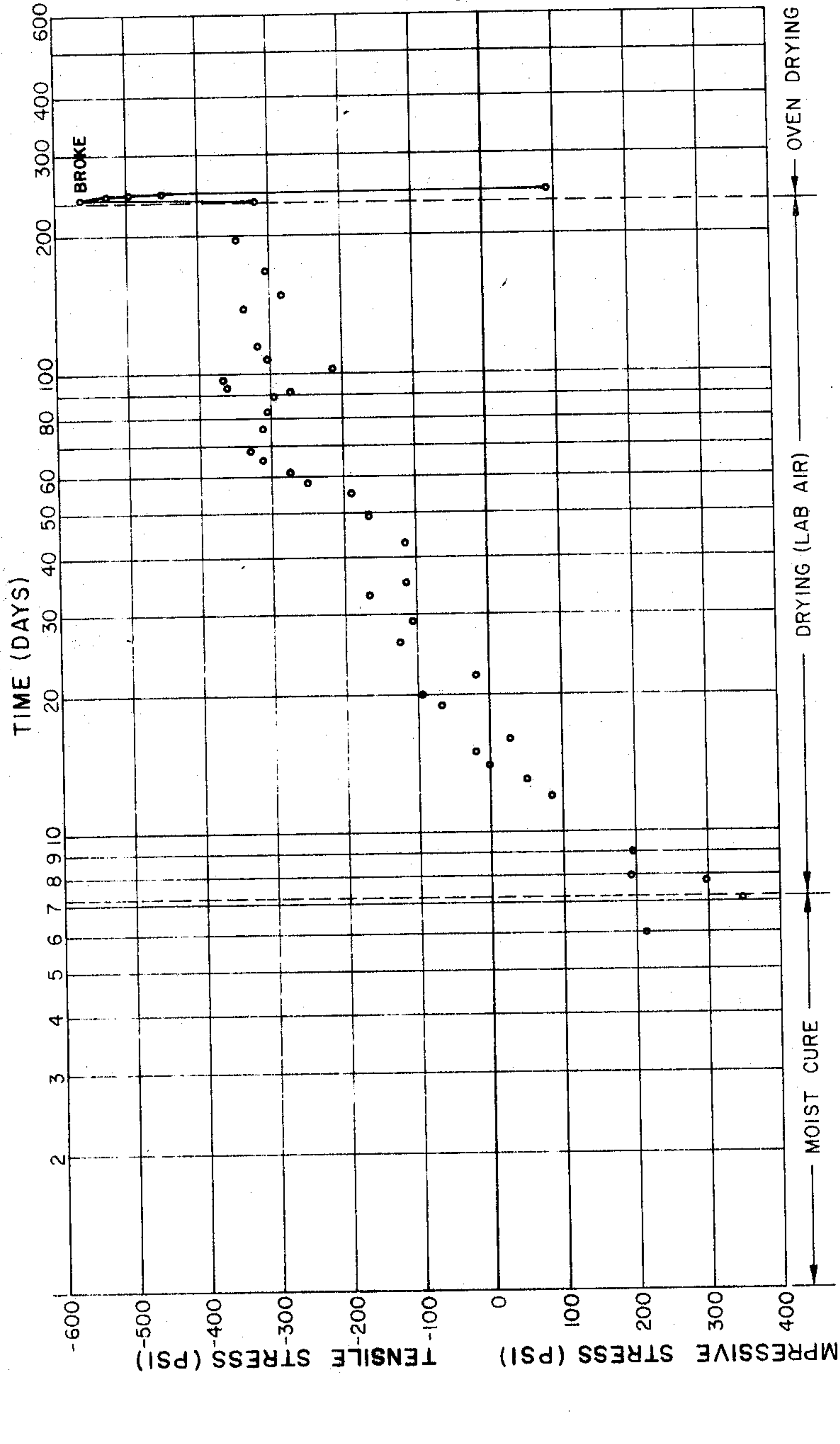
Figure 18



Scale: 1" = 5"

RESTRAINED CONCRETE SHRINKAGE BAR

Figure 19



CONCRETE STRESS-TIME CURVE FOR BEAMS
SHRINKAGE COMPENSATED CEMENT # 1
(RESTRAINED SHRINKAGE BEAMS)

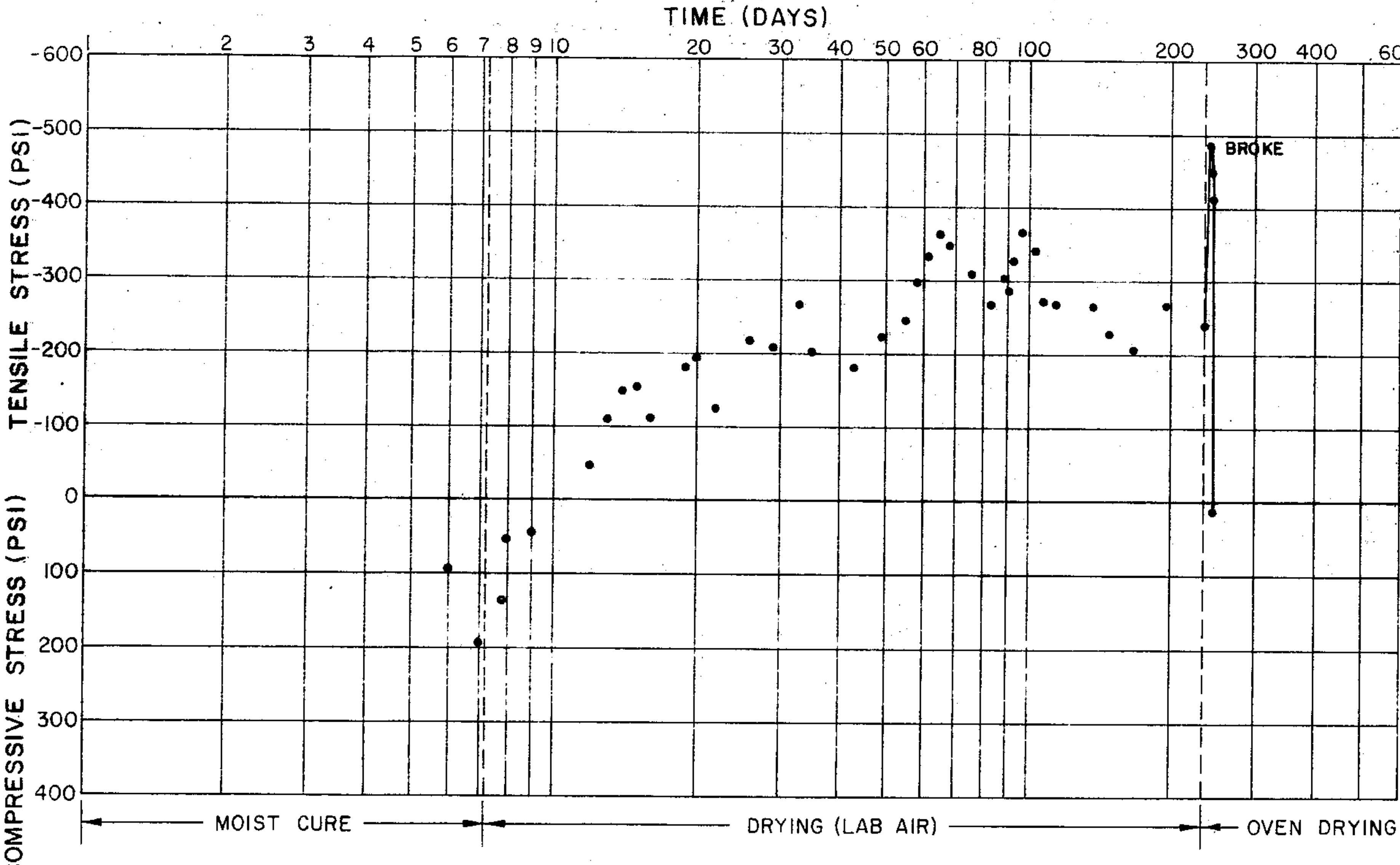
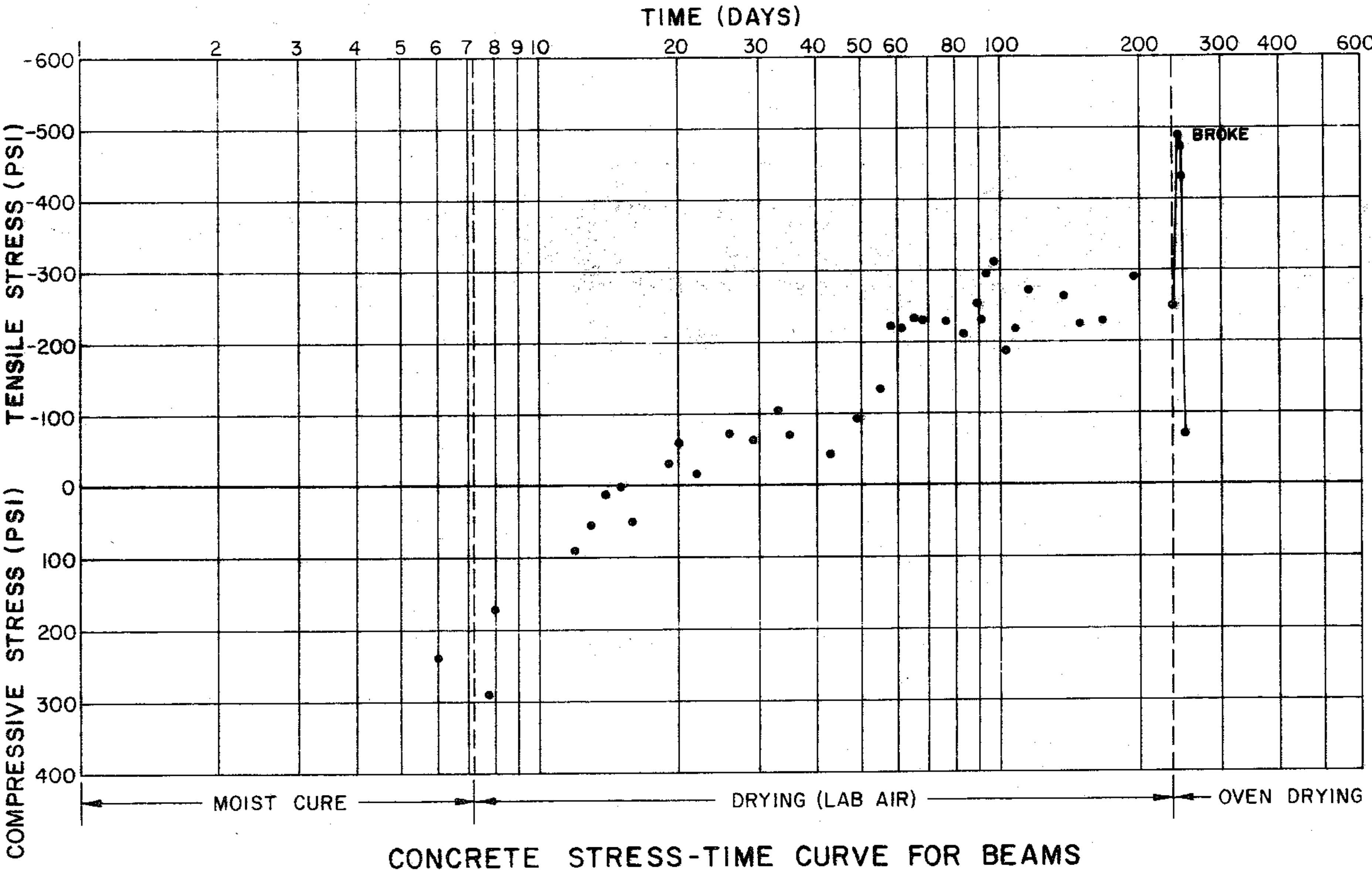


Figure 20

CONCRETE STRESS-TIME CURVE FOR BEAMS
TYPE II CEMENT
(RESTRAINED SHRINKAGE BEAMS)

Figure 21



CONCRETE STRESS-TIME CURVE FOR BEAMS
SHRINKAGE COMPENSATED CEMENT # 2
(RESTRAINED SHRINKAGE BEAMS)

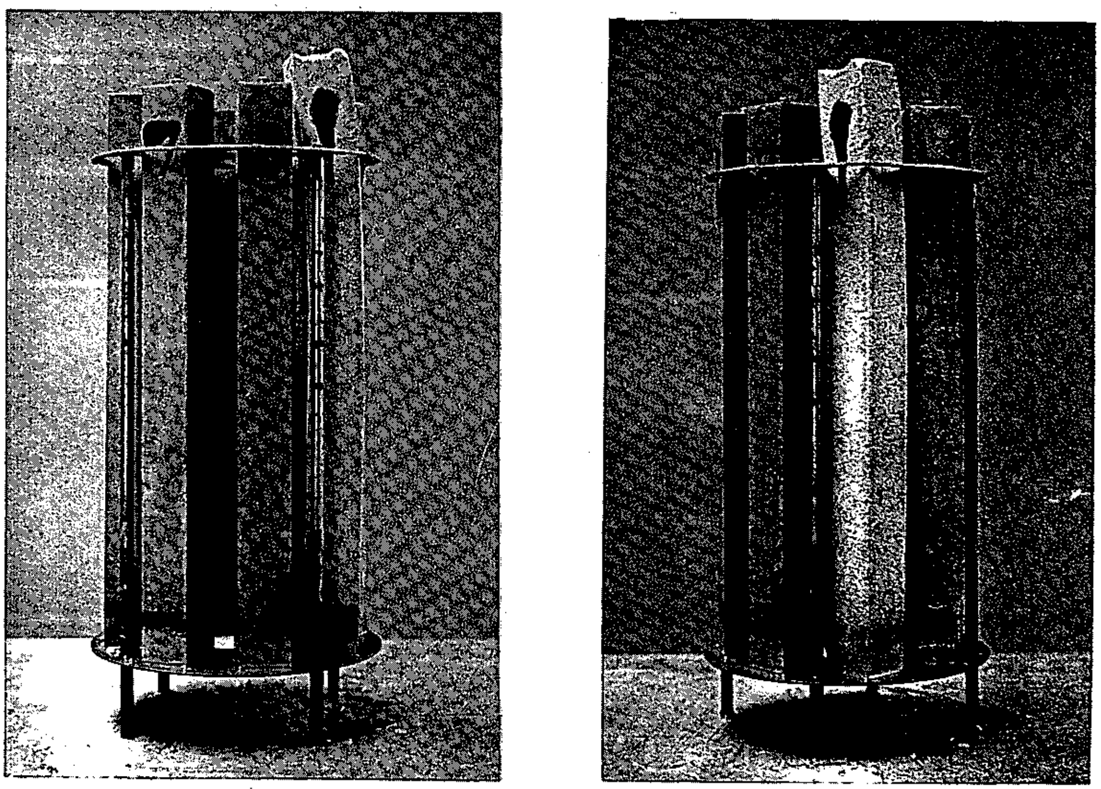


Figure 22

The bar marked 1 is made with the no. 2 shrinkage compensated cement. The bar expanded excessively in the autoclave. The other bars are made with Type II cement.